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Effect of Stitching on Plain and Open-hole Strength of CFRP Laminates

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Abstract

Experimental and analytical investigation is conducted to explore the effects of stitching on plain (without hole) and open-hole compressive and tensile strength of uniweave T300/QY9512 laminates under different environmental conditions (20 ºC/dry and wet, 150 ºC/dry and wet). Strength performance of stitched composite laminates is also studied using finite element analysis (FEA) model and compared with the experimental results to validate the model. It is found that under similar environmental conditions, the open-hole compressive strength of stitched laminate is decreased and open-hole tensile strength increased as compared to the unstitched laminates. Predicted tensile and compressive strengths are found to be in a good agreement with the test results and the relative error in all cases is less than 15%.

Keywords: composite materials; stitching; finite element method; resin film infusion; hygrothermal

1. Introduction

In recent years, carbon-fibre reinforced plastics (CFRP) have received considerable attention as structural materials due to their high strength-to-weight ratio in relation to conventional metals such as steel and aluminum. Combinations of constituent material characteristics make polymer-based composites a subject of tremendous interest in the aerospace, construction and automobile industries. The load carrying capacity of composite structures is limited by its low strain to failure. Laminated composite materials generally have low strength in thickness direction. Since delamination is one of the major forms of damage in laminated composites, stitching is performed to increase through the thickness strength. Stitching is a method of joining composite laminate plies through the use of various thread materials. The stitch fibres act as bridging elements much like steel reinforcement bars in concrete keeping the plies from separating from each other. Through-thickness stitching improves the out of plane strength of composite laminates by an order of magnitude [1-2]. This improved through thickness strength may allow the use of composites in critical wing and fuselage structures. Considerable effort has been devoted to assess the potential applications of stitched laminates in aircraft structures such as fuselages, wing panels and blade stiffened components. Stitching has been successfully applied to the pressure bulkhead of Airbus A380. In fact the aerospace industry is showing more interest in stitching uniweave, Liba warp-knit and braided fabric composites for the use in new generation primary structures for commercial aircraft, such as fuselages and wings [1-3].

On the other hand, stitching reduces the in-plane properties of laminates. Neither the stitching needles nor the stitching yarns are small relative to the tows within the plies of in-plane fibers and both of them

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pass through the laminate thickness with relatively large forces [1-2]. Significant distortions of both in-plane fibers and fibers within stitches do occur during stitching and subsequent laminate consolidation. Composites are also susceptible to heat and moisture when operating in harsh and changing environmental conditions. Thermo-mechanical properties of composite laminates can be degraded by the absorption of moisture from humid environment [4-5]. This moisture absorption leads to changes in the thermo-physical, mechanical and chemical characteristics of the resin matrix by plasticization and hydrolysis [6-8]. Moisture absorption and exposure to high temperature causes a reduction of in-plane properties of composite laminates [9-10]. The ratio of the moisture absorption in composite laminates is accelerated by the presence of cracks and voids in the laminate [11-12].

In order to utilize the composite materials effectively, their behavior under various conditions needs to be determined. The in-plane compressive strength is the most extensively studied mechanical property of stitched composite. Effects of stitching on the in-plane tensile properties have also been studied for a variety of fiber reinforce plastic (FRP) composites including carbon, glass and Kevlar fiber laminates. The growing amount of data on the in-plane mechanical properties of stitched laminates is backing the advances in stitching technology. However, a literature review by Mouritz, et al. [1] revealed that despite of the large amount of in-plane mechanical property data for stitched laminates, significant deficiencies still remain in our understanding of the mechanisms by which stitching affects stiffness, strength and fatigue performance. One major problem is the apparent contradictions between different studies on how stitching alters the in-plane properties.

A number of papers reported that stitching do not significantly affect the strength of CFRP composite [1-2]. Many of the reports appear contradictory with some observing no change or a slight improvement in the tensile properties because of stitching while other studies report reductions in the properties of varying magnitude.

In this study, an attempt has been made to explore the effect of stitching on plain and open-hole compressive and tensile strength of uniweave T300/QY9512 laminates under different environmental conditions (20 ºC/dry, 20 ºC/wet, 150 ºC/dry and 150 ºC/wet). The wet condition is to dip the specimens in 71±10 ºC in distilled water for seven days. Specimens are subjected to uniaxial tensile and compressive loading. Stitching effects are studied by comparing test results of stitched laminates to the test results of unstitched laminates under the same environmental conditions. This work is based upon the previous research about compressive strength of CFRP stitched laminates [5]. Strength performance of stitched composite laminates is studied using an finite element analysis (FEA) model and compared with experimental results to validate the accuracy of the FEA model. In this research work, the study regarding the contribution of moisture gain of Kevlar-29 and epoxy QY9512 upon performance of CFRP stitched laminates is not performed.

2. Experimental Work

2.1. Material and specimens

Tests were conducted on several unstitched and stitched composite specimens to find the plain (without hole) and open-hole compressive and tensile strength of laminates. The specimens were made of T300/QY9512 (carbon-fibre-reinforced bismaleimide (BMI)) using resin film infusion (RFI). Fibre volume fraction was about 62%. Fiber volume fraction of stitched laminates was measured in a separate research work by the author [13]. At the time of preparation of test specimens, standards for stitched composite laminates were not available. Therefore American society for testing materials (ASTM) standards for unstitched composite laminates were followed as a reference. Three kinds of stacking sequences A, B and C were used, as given in Table 1. The properties of the material are shown in Table 2[14].

Table 1 Lay-up of laminates

Lay-up type	Stacking sequence	Layer number
A	$[45/0/-45/90]_{4s}$	32
B	$[0/45/0/-45/90/-45/0/45/0]_{2s}$	36
C	$[90/45/90/-45/0/-45/90/45/90]_{2s}$	36

Table 2 Properties of T300/QY9512

Moduli	Value /GPa	Strength	Value /MPa
E_{11}	123.60	X_t	1 546.7
E_{22}	8.53	X_c	1 464.0
G_{12}	4.50	Y_t	47.9
v_{12}	0.32	Y_c	190.6
		S	90.0

The laminates were stitched with a modified chain stitching machine. A 1 400 denier Kevlar-29 yarn was used for bobbin thread; a 400 denier Kevlar-29 yarn was used for needle thread (see Fig. 1). Stitching was carried out in three directions of 0°, 45° and 90° relative to 0° direction. The stitch line spacing was 5 mm and stitch step was 3 mm or 5 mm. All the laminates were ultrasonically C-scanned to check for defects prior to testing; any defective laminates were rejected. Tests were performed on a MTS880-500 kN servo hydraulic testing machine.

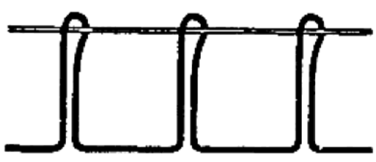


Fig. 1 Modified chain stitching model.

2.2. Compression testing

2.2.1. Plain compression specimen

The stacking sequence for compression test of plain specimens was $[45/0/–45/90]_{4s}$, $[0/45/0/–45/90/–45/0/45/0]_{2s}$ and $[90/45/90/–45/0/–45/90/45/90]_{2s}$, respectively. The stitching direction was 0°, 45° and 90°. The stitch step was set at 3 mm and stitch line spacing was 5 mm. Test conditions were 20 ºC/dry, 150 ºC/dry and 150 ºC/wet. Compression test specimens were having a length of 45 mm and width of 40 mm. The modulus of composite laminates was reduced under hygrothermal environment, therefore the length of compression specimens were kept shorter to avoid buckling. No anti-buckling guides were used for compression testing. Thickness of specimens varied from 4.49 mm to 4.59 mm for various configurations.

2.2.2. Open-hole compression specimen

Open-hole compression test was conducted for A type $[45/0/–45/90]_{4s}$ lay-up specimens. The size of the specimen was 75 mm × 50 mm and the diameter of the hole was 12.5 mm. The width/diameter (W/D) ratio was 4. Stitching was performed in 0°, 45° and 90° directions; stitch step and stitch spacing was set to 5 mm.

2.3. Tensile testing

2.3.1. Plain tensile specimen

Tensile strength test was conducted for A type stitched and unstitched laminates. The specimen dimension was 230 mm long by 25 mm wide. The test conditions were 20 ºC/dry and 20 ºC/wet.

2.3.2. Open-hole tensile specimen

Open-hole tensile tests were performed on A type $[45/0/–45/90]_{4s}$ laminates. The size of the specimen was 270 mm × 38 mm and the diameter of the hole was 6 mm. The width/diameter (W/D) ratio was 6.33. The test conditions were 20 ºC (dry and wet) and 150 ºC (dry and wet).

3. Experimental Results and Discussion

3.1. Compression strength of plain specimens

The compression strength of the specimens in different test conditions is brought into comparison (Tables 3-5). In the tables, σ_c is the compression strength. It is found that the reduction in compressive strength of unstitched C type laminates under 150 ºC/dry and 150 ºC/wet condition is more than that of A and B type laminates. However, this reduction is smaller for stitched C type laminates under the same environmental conditions. In general, the compressive strength of C type laminates still remains smaller as compared to A and B lay-up. This is probably due to the lower number of 0° layers in C type laminates. Figure 2 illustrates the effect of stitching on compressive strength of A, B and C layups, σ and $\sigma_{\text{unstitched}}$ mean the stitched/unstitched laminate compression strength respectively. Figure 3 shows the photographs of some specimens.

Table 3 Compression strength for A lay-up laminates

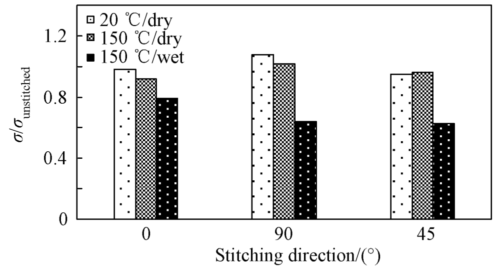
Stitching direction/(°)	Number of test	Condition	Temperature/ ºC	σ_c / MPa	Standard deviation/ MPa
Unstitched	3	Wet	150	395.7	17.2
	4	Dry	20	545.1	22.4
	3	Dry	150	469.5	15.6
0	3	Wet	150	313.1	21.5
	5	Dry	20	533.6	47.9
	3	Dry	150	431.9	37.5
90	3	Wet	150	253.1	19.2
	4	Dry	20	587.1	26.8
	3	`Dry	150	476.7	46.7
45	3	Wet	150	249.0	13.6
	5	Dry	20	519.1	16.8
	4	Dry	150	452.2	16.0

Table 4 Compression strength for B lay-up laminates

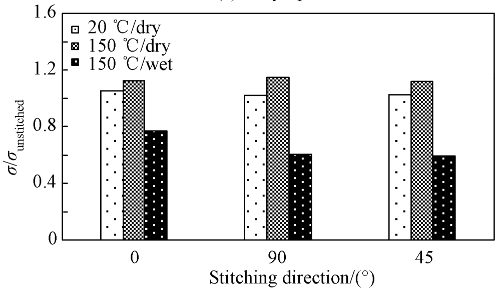
Stitching direction/(°)	Number of test	Condition	Temperature / ºC	σ_c/ MPa	Standard deviation/ MPa
Unstitched	3	Wet	150	448.2	19.2
	4	Dry	20	575.9	23.6
	3	Dry	150	494.1	28.7
0	3	Wet	150	343.7	21.7
	5	Dry	20	603.2	48.6
	3	Dry	150	555.2	60.2
90	3	Wet	150	271.3	34.2
	4	Dry	20	586.1	29.7
	3	Dry	150	568.5	32.6
45	3	Wet	150	263.5	32.6
	5	Dry	20	590.9	29.3
	4	Dry	150	551.4	22.2

Table 5 Compression strength for C lay-up laminates

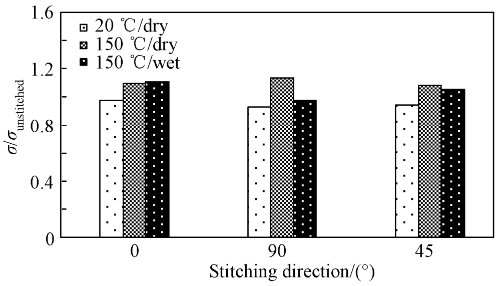
Stitching direction/(°)	Number of test	Condition	Temperature / ºC	σ_c/ MPa	Standard deviation/ MPa
Unstitched	3	Wet	150	228.1	16.3
	4	Dry	20	421.2	28.2
	3	Dry	150	335.5	15.6
0	3	Wet	150	252.3	17.4
	5	Dry	20	411.8	12.6
	3	Dry	150	367.8	29.3
90	3	Wet	150	222.3	18.6
	4	Dry	20	390.4	14.6
	3	Dry	150	381.2	6.63
45	3	Wet	150	241.5	5.96
	5	Dry	20	395.7	16.3
	3	Dry	150	362.7	26.3



(a) A lay-up laminates

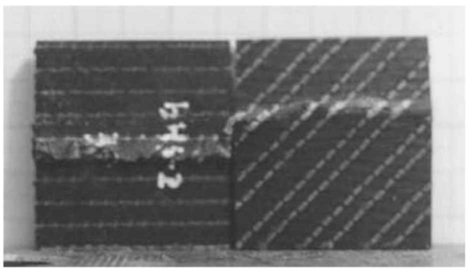


(b) B lay-up laminates



(c) C lay-up laminates

Fig. 2 Stitching effects on compression strength.


(a) 90° and 45° stitching directions for A lay-up laminates in 20 ℃/dry environment

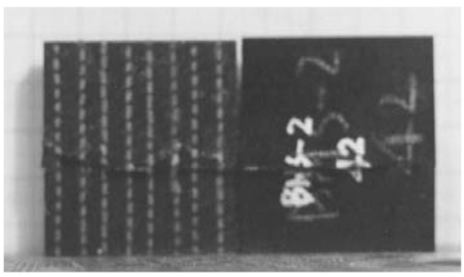

(b) Unstitched and 90° stitching direction for B lay-up laminates in 150 ℃/wet environment

Fig. 3 Photographs of compression specimens.

Through comparison between unstitched and stitched laminates, it is found that the effect of stitching under 20 ºC/dry condition appears to improve the laminate compressive strength in a few laminates while reducing in some other laminates. However, the amount of reduction or improvement is insignificant in both cases.

Under high temperature condition (150 ºC/dry), stitching has a different impact on compressive properties of laminates depending upon their stacking sequence. In case of the A lay-up laminates, stitching reduces the compressive strength by about 3%-8%, while it improves the compressive strength of B and C lay-up laminates up to 12%.

Under hygrothermal conditions (150 ºC/wet), stitching causes a 20%-40% decrease in compressive strength of A and B layups and improves the compressive strength of C type laminates up to 10%.

The number of 0° plies in A and B type laminates is higher (25% and 44% respectively) than that for C type laminates (11%). During stitching process, holes created by stitching needle allow more water absorption that leads to more plasticization thus causing debonding in the 0° plies. This effect becomes more severe for the laminates having a large number of 0° plies and is probably the reason for the reduced compressive strength of A and B type laminates. In case of C type laminates, the reduction in compressive strength is almost the same for both stitched and unstitched laminates under hygrothermal (150 ºC/wet) conditions and compressive strength of stitched laminates is not much decreased under the effect of high temperature and absorbed moisture.

In carbon-reinforced composites, oxidation of matrix polymers is strongly influenced by geometry and ply orientation. Matrix oxidation is dominated by the outer surface and the fibre-matrix interface, progressing inward from exposed edges along the fibre. The nature of the fibre-matrix interface region and the influence of fibre coatings or sizing are critical in limiting oxidation of the composite. Hygrothermal behavior of a composite laminate is dependent upon various parameters including the properties of matrix and fibres, ply thickness and lay-up stacking sequence. It means that, the diffusivity is determined by the orientation and ply sequence of the composite laminates and this is the key factor in explaining the effects of different environmental conditions on the compressive strength for different lay-up sequences.

It may now be stated that stitching might improve the compressive failure strength of composite laminates. However, under the combined effects of absorbed moisture and high temperature, compressive strength of stitched laminates can either be improved or reduced depending on ply orientation and lay-up staking sequence.

3.2. *Compression strength of open-hole specimen*

Test results given in Table 6 show that stitching has a beneficial effect on open-hole compression strength under 20 °C/dry, while hygrothermal environment has no significant effect on the compression failure mechanisms of stitched and unstitched specimens.

Table 6 Open hole compression strength for A lay-up laminates

Stitching direction/(°)	Number of tests	Condition	Temperature/ °C	σ_c / MPa	Standard deviation/ MPa
Unstitched	5	Dry	20	209.7	10.60
	5	Wet	150	145.7	4.01
0	3	Dry	20	268.7	9.41
	3	Wet	150	146.8	5.19
90	5	Dry	20	249.1	16.80
	5	Wet	150	161.8	8.39
45	3	Dry	20	286.9	3.92
	2	Dry	150	219.4	2.31
	4	Wet	20	269.4	3.60
	3	Wet	150	146.2	4.68

Unstitched specimens fail due to the delamination between plies under compression. The open-hole compressive damage mode of the stitched laminate is due to the in-plane fiber failure. A kink band is formed first at the edge of the hole due to stress concentration. As the load increases the damage band propagates away from the edge of the hole thus causing the final failure. The in-plane shear tends to result in debonding of matrix and the fibre. Matrix concentration and fiber bending are present in stitch region therefore fibers may easily fail under the effect of hygrothermal environment. The test results of open-hole compressive strength of laminates are illustrated in Fig. 4. Figure 5 shows the photographs of some specimens.

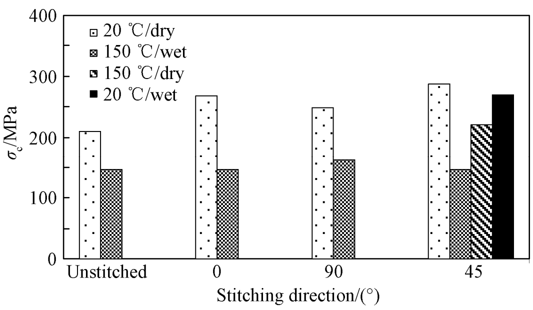
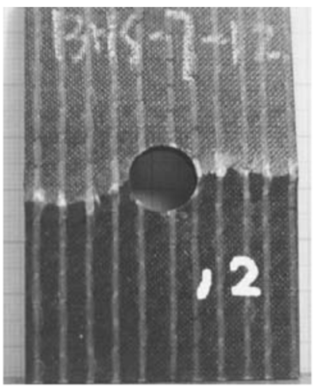


Fig. 4 Open-hole compression strength for A lay-up laminates.



(a) 0° stitching direction, 20 ℃/dry

(b) 45° stitching direction, 150 ℃/dry

(c) 90° stitching direction, 20 ℃/dry

Fig. 5 Photographs of open-hole compression for A lay-up laminates.

3.3. *Tensile strength of plain specimen*

The results given in Table 7 show that a wet environment has no effect on the tensile strength of unstitched laminates, but improves the tensile strength of stitched laminates up to 12%, σ_t is the tensile strength. The results are illustrated in Fig. 6. The specimens always fail at the stitched nodes under both test conditions of 20 ºC/dry, 20 ºC/wet. Figure 7 shows the photographs of some specimens failing under tensile load.

Table 7 Tensile strength test results for $[45/0/-45/90]_{4s}$ laminates (20 ºC)

Stitching direction/(°)	Number of tests	Condition	Temperature / °C	σ_t/ MPa	Standard deviation/ MPa
Unstitched	3	Dry	20	404	16.2
	3	Wet	20	399	15.6
0	3	Dry	20	376	21.5
	3	Wet	20	409	19.5
90	3	Dry	20	367	19.2
	3	Wet	20	411	23.7
45	3	Dry	20	367	13.6
	3	Wet	20	379	16.0

Under 20 ºC/dry condition, stitching decreases the tensile strength of the stitched laminates up to 9%. The reduction in tensile strength is probably due to the crimping of the fibre bundles caused by stitching,

which is obvious near the stitching nodes. Misalignment of fibres leads to significant stress concentration; therefore, stitched laminates always fail in the stitch node regions also called resin pockets.

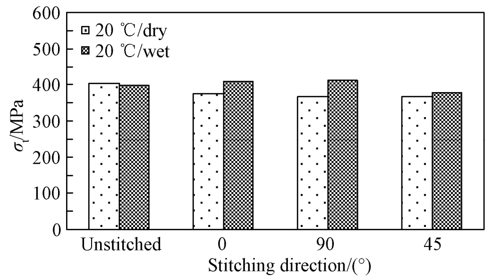
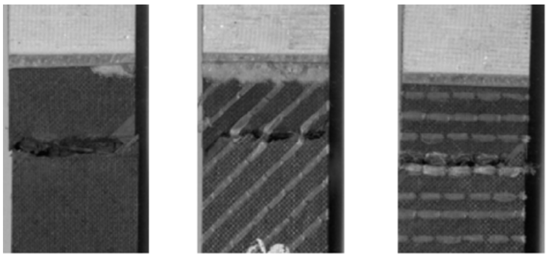


Fig. 6 Tension strength for A lay-up laminates.



(a) Unstitched (b) 45° stitching direction (c) 90° stitching direction

Fig. 7 Photographs of compression for A lay-up laminates, 20 °C/wet.

Under 20 ºC/wet condition, the effect of stitching on tensile strength seems to be very slight (±4%) which might be due to the partial recovery of tensile strength as a result of moisture absorption. This improvement probably results from the moisture absorption of ±45° plies. For the laminates subject to tensile load, the force transfer between layers is controlled by ±45° plies. In-plane shear strain is higher under the high humidity conditions. Therefore, under wet environment, the fibers of ±45° plies with higher in-plane shear strain tend to align with the loading direction and cause an increase in tensile strength of the stitched laminates.

3.4. Tensile strength of open-hole specimen

Table 8 shows the test results open-hole specimen tensile strength and Fig. 8 illustrates those results. Photographs of open-hole tensile test specimen are shown in Figs. 9-10. A close observation of the damage pattern of stitched specimens shows that, when the root of the hole is near to the a stitching node, the specimens always fail at the stitched nodes; whereas, when the hole is located between two adjacent stitch lines, the crack is in the middle of two parallel stitch lines.

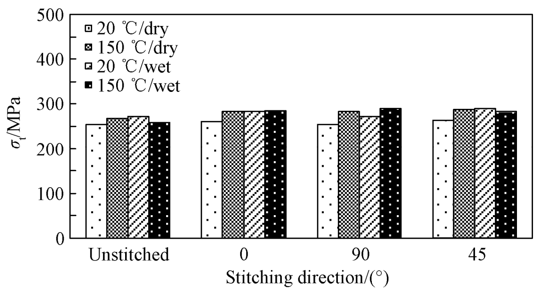
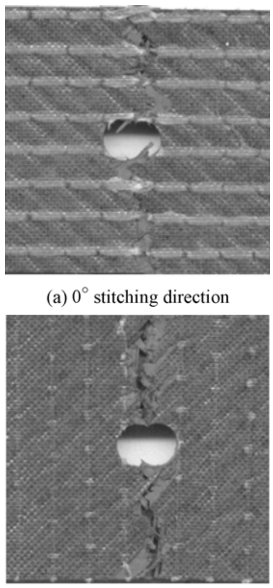


Fig. 8 Open hole tension strength for A lay-up laminates.

Table 8 Open hole tension strength for A lay-up laminates

Stitching direction/(°)	Number of tests	Condition	Temperature / °C	σ_t/ MPa	Standard deviation/ MPa
Unstitched	3	Dry	20	254	17.2
	3	Dry	150	268	22.4
	3	Wet	20	272	18.6
	3	Wet	150	259	15.6
0	3	Dry	20	261	21.5
	3	Dry	150	283	47.9
	3	Wet	20	284	29.3
	3	Wet	150	286	37.5
90	3	Dry	20	254	19.2
	3	Dry	150	283	26.8
	3	Wet	20	272	27.5
	3	Wet	150	290	46.7
45	3	Dry	20	264	13.6
	3	Dry	150	287	16.8
	3	Wet	20	289	15.9
	3	Wet	150	284	16.0

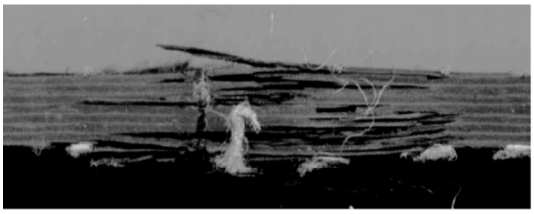


(a) 0° stitching direction

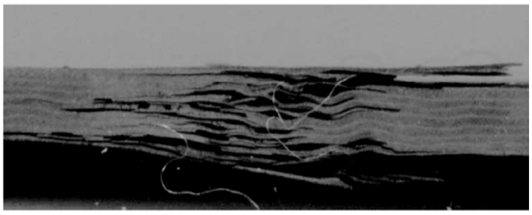
(b) 90° stitching direction

Fig. 9 Photographs of open-hole tension for A lay-up laminates, 150 °C/wet.

The tensile strength of stitched laminates is obviously higher than unstitched laminates. On the other hand the in-plane fibre distortions, breakage of in-plane fibres and resin pockets created due to stitching have a detrimental effect on the in-plane mechanical properties. When the stitch node is near the edge of the hole, the stress concentration level at the edge of the hole is reduced. Also, when the stitch node is near the edge of the hole, moisture reduces the stress concentration level at the edge of the hole. It is found that, the effect of stitching is not significant in hot/wet environment.



(a) Stitched



(b) Unstitched

Fig. 10 Open-hole tension specimen damage pattern of A lay-up laminates, 150 °C/wet.

4. Prediction of Strength Performance Using FEA Model

The strength performance of stitched composite laminates is studied using the FEA model. Numerical data are compared with experimental results to validate the accuracy of the FEA model. In-plane bending of fibres and resin rich regions created by stitching are common around the stitching thread in stitched composite laminates; therefore, we must consider these characteristics while analyzing in-plane strength of stitched laminates macroscopically. As fibre fracture and bending in z-direction (thickness direction) caused by stitching is very small and only exists at the surface layer, it was neglected. Three important factors are considered for establishing the model [14]:

1) In-plane bending of fibre caused by stitching;
2) Resin rich regions around stitching thread;
3) Reinforcement of stitching thread in z-direction.

4.1. FEA model

The FEA model is created using MSC PATRAN 2004. The change of the in-plane performance of composite laminates due to stitching was studied using a model established by Gui [15]. The model can be used to analyze the elastic constants of laminates and single layers macroscopically. Due to the difference of the stitching effect at various locations in the laminate, there is a limitation for the analysis of macroscopic strength. Based on the model, elastic-matrix-field function was formulated and an FEA model was established which could be used to analyze the strength of stitched laminates [14].

For stitched composite laminates, in-plane bending of fibre due to stitching process is different for each layer. Therefore, it is necessary to divide the model layer-by-layer and use a micro mechanics analysis model, which is effective for the improvement of accuracy. This study uses 3-D element with 8 nodes to divide laminates layer-by-layer. As a result, the element size in z-direction is very small. The in-plane mesh is very dense, which results in a larger stiffness matrix as shown in Fig. 11. At the left side of model; 3-D elements with 8 nodes (fine mesh) are used whereas at the right side the same elements are used with a coarse mesh. 3-D elements with 13 nodes are used to connect the coarse and fine meshes at the interface.

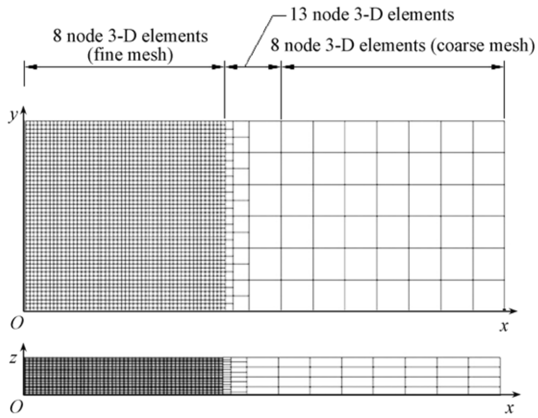


Fig. 11 Varying mesh density in FEA model.

Additionally, the stitching thread throughout the z-direction is placed in laminates according to the stitching technique used. Stitching thread is under axial and shear stress on its cross-section. A beam element is used to simulate the reinforcement by the thread in z-direction. The number of beam elements in thickness direction at a certain nodal point is equal to the number of layers in the model. To simulate the in-plane fibre bending and resin pockets created due to stitching, the model establishes elastic-matrix-field function in the region where 3-D elements with 8 nodes are used. This effect is not considered for the region where the 3-D elements with 13 nodes are used.

4.1.1. 3-D Element with 8 nodes

3-D element with 8 nodes is shown in Fig. 12. (ξ, η, ζ) is the local coordinates, the element shape functions are expressed by natural coordinates in the natural system of coordinates:

$$N_i = \frac{1}{8}(1+xx_i)(1+hh_i)(1+zz_i) \quad (i=1,2,\cdots,8) \tag{1}$$

where x, h, z all are the elements.

The strain of element is given by

$$\boldsymbol{\varepsilon} = \boldsymbol{B\delta} \tag{2}$$

where

$$\boldsymbol{\varepsilon}^{\mathrm{T}}=[\varepsilon_{1x}\ \varepsilon_{1y}\ \varepsilon_{1z}\ \varepsilon_{1yz}\ \varepsilon_{1zx}\ \varepsilon_{1xy},\varepsilon_{2x}\ \varepsilon_{2y}\ \varepsilon_{2z}\ \varepsilon_{2yz}\ \varepsilon_{2zx}\ \varepsilon_{2xy},\ldots,\varepsilon_{8x}\ \varepsilon_{8y}\ \varepsilon_{8z}\ \varepsilon_{8yz}\ \varepsilon_{8zx}\ \varepsilon_{8xy}] \tag{3}$$

$$\boldsymbol{\delta}^{\mathrm{T}}=\left[u_1\ v_1\ w_1,u_2\ v_2\ w_2,\cdots,u_8\ v_8\ w_8\right] \tag{4}$$

where u,v and w are the displacement in x,y and z direction, with the element strain matrix

$$\boldsymbol{B}=[\boldsymbol{B}_1\quad \boldsymbol{B}_2\quad \cdots\quad \boldsymbol{B}_8] \tag{5}$$

And

$$\boldsymbol{B}_i=\begin{bmatrix}\frac{\partial N_i}{\partial x} & 0 & 0\\ 0 & \frac{\partial N_i}{\partial y} & 0\\ 0 & 0 & \frac{\partial N_i}{\partial z}\\ \frac{\partial N_i}{\partial z} & 0 & \frac{\partial N_i}{\partial x}\\ 0 & \frac{\partial N_i}{\partial z} & \frac{\partial N_i}{\partial y}\\ \frac{\partial N_i}{\partial y} & \frac{\partial N_i}{\partial x} & 0\end{bmatrix}(i=1,2,\cdots,8) \tag{6}$$

$$\boldsymbol{K}=\int_{-1}^{1}\int_{-1}^{1}\int_{-1}^{1}\boldsymbol{B}^{\mathrm{T}}\boldsymbol{D}\,\boldsymbol{B}\det\boldsymbol{J}\mathrm{d}\zeta\mathrm{d}\xi\mathrm{d}\eta \tag{7}$$

where $\boldsymbol{J}$ is the Jacobian matrix, and $\boldsymbol{D}$ the elastic matrix:

$$\boldsymbol{D}=\boldsymbol{TCT}^{\mathrm{T}} \tag{8}$$

where $\boldsymbol{T}$ is the coordinate transformation matrix, and $\boldsymbol{C}$ stiffness matrix.

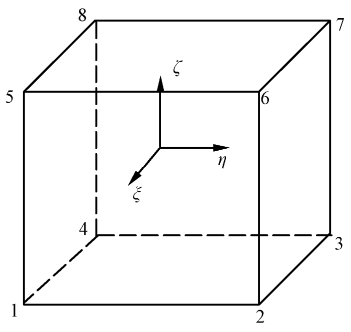


Fig. 12 3-D element with 8 nodes.

In this study, the laminate stiffness is a function of (x, y) because of the in-plane influence caused by stitching. After transformation, $\boldsymbol{D}$ is a function of (ξ,η).

4.1.2. Beam element

The beam element is shown in Fig. 13. Considering the matching of degrees of freedom (DOF) between beam element and 3-D element with 8 nodes, the stiffness matrix of the beam element is consolidated during the calculation. The independent DOF is deleted. Because in this study the thread is simulated by the beam, the model assumes a rectangular cross section and the width of rectangle is twice of thread's diameters which represents two threads side by side and height is one of the thread's diameter. The stiffness matrix of the beam element is

$$\boldsymbol{K}=\begin{bmatrix}\frac{EA}{L} & & & & & \\ 0 & \frac{12EJ_z}{l^3} & & \text{SYM} & & \\ 0 & 0 & \frac{12EJ_y}{l^3} & & & \\ -\frac{EA}{L} & 0 & 0 & \frac{EA}{L} & & \\ 0 & -\frac{12EJ_z}{l^3} & 0 & 0 & \frac{12EJ_z}{l^3} & \\ 0 & 0 & -\frac{12EJ_y}{l^3} & 0 & 0 & \frac{12EJ_y}{l^3}\end{bmatrix} \tag{9}$$

where J_y and J_z are inertia moments of cross section, E is the modulues. The DOF vector corresponding to the stiffness matrix is

$$\boldsymbol{\delta}^{\mathrm{T}}=\left[u_i\ v_i\ w_i,u_j\ v_j\ w_j\right] \tag{10}$$

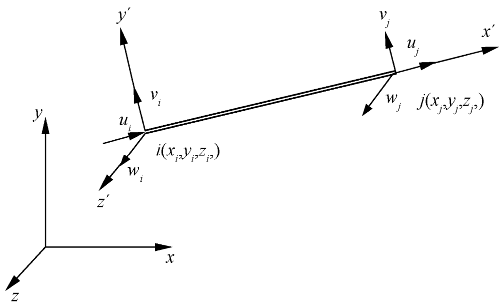


Fig. 13 Beam element.

4.1.3. 3-D Element with 13 nodes

This kind of element is different from the 3-D element with 8 nodes. There are more nodes on the surface connecting to the 3-D element with 13 nodes as shown in Fig. 14.

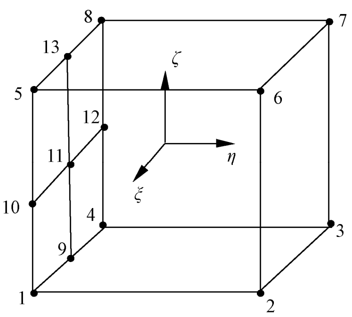


Fig. 14 3-D element with 13 nodes.

The shape functions in the natural system of coordinates are given by

$$N_i = \frac{1}{8}(1+\xi\xi_i)(1+\eta\eta_i)(1+\zeta\zeta_i)\ (i=2, 3, 6, 7) \quad (11)$$

$$N_i = \frac{1}{8}\xi_i\xi\zeta_i\zeta(1+\xi_i\xi)(1+\eta_i\eta)(1+\zeta_i\zeta)$$

$$(i=1, 4, 5, 8) \quad (12)$$

$$N_i = \frac{1}{4}\zeta\zeta_i(1-\xi^2)(1+\eta\eta_i)(1+\zeta\zeta_i)\ (i=9, 13) \quad (13)$$

$$N_i = \frac{1}{4}\xi\xi_i(1-\zeta^2)(1+\eta\eta_i)(1+\xi\xi_i) \quad (i=10, 12) \quad (14)$$

$$N_i = \frac{1}{2}(1-\zeta^2)(1+\eta\eta_i)(1-\xi^2) \quad (i=11) \quad (15)$$

When fibre is damaged under tension load, E_1 (normal modulus in 1 direction)will be decreased. When matrix is damaged because of tension or shear, E_2(normal modulus in 2 direction), G_{12}, G_{23} (shear modulus in 1-2 and 2-3 direction)will be attenuated. When the thread is damaged because of tension, it is not assembled to the stiffness matrix of the laminate.

Due to the presence of the stitching thread in a laminate, fibres fluctuate periodically in the plane. It is assumed that fibres bend regularly with the shape of sine function. Based on this assumption, a fluctuation function is established, which could be used to find the content, direction and elastic-matrix-field function of fibre at any location in the whole plane. While establishing the function, the model is based on the assumption that at stitching node, the thread would be parallel to the stitching direction.

4.2. Damage criteria

This study uses Hashin's criteria to detect in-plane damage in the laminates [16-17].

Fibre tensile fracture, $\sigma_{11}\geq 0$:

$$\left(\frac{\sigma_{11}}{X_\mathrm{T}}\right)^2 + \frac{1}{S_\mathrm{C}^2}\left(\sigma_{12}^2+\sigma_{13}^2\right) = 1 \quad (16)$$

where σ_{11} is the represent principal stress in direction 1, σ_{12} and σ_{13} are the shear stresses, X_T is the tensile strength in direction 1, S_C the shear strength.

Fibre compressing fracture, $\sigma_{11}<0$:

$$-\left(\frac{\sigma_{11}}{X_\mathrm{C}}\right) = 1 \quad (17)$$

where X_C is the compressive strength in direction 1.

Matrix tensile fracture or shear fracture, $\sigma_{22}+\sigma_{33}\geq 0$:

$$\left(\frac{\sigma_{22}+\sigma_{33}}{Y_\mathrm{T}}\right)^2 + \frac{\sigma_{12}^2+\sigma_{13}^2+\sigma_{23}^2-\sigma_{22}\sigma_{33}}{S_\mathrm{C}^2} = 1 \quad (18)$$

where σ_{22} and σ_{33} are the represent principal stress in direction 2 and 3, σ_{23} is the shear stress, Y_T the tensile strength in direction 2.

Matrix compression fracture or shear fracture, $\sigma_{22}+\sigma_{33}<0$:

$$\frac{1}{Y_\mathrm{C}}\left[\left(\frac{Y_\mathrm{C}}{2S_\mathrm{C}}\right)^2-1\right]\left(\sigma_{22}+\sigma_{33}\right)+\frac{\left(\sigma_{22}+\sigma_{33}\right)^2}{4S_\mathrm{C}^2}+$$

$$\frac{\sigma_{12}^2+\sigma_{13}^2+\sigma_{23}^2-\sigma_{22}\sigma_{33}}{S_\mathrm{C}^2} = 1 \quad (19)$$

where Y_C is the compressive strength in direction 2.

4.3. Prediction of compression strength

The compression strength of different unstitched and stitched laminates under different environmental conditions is predicted and compared to the test results. Using the analytical results the relation between displacement and increasing load is investigated. Figure 15 illustrates the (stress vs displacement) diagram for the A lay-up 0° stitched laminates under compressive load. The relation between increasing load and displacement is linear up to a certain point where the damage is initiated in the laminates. At this point the stiffness matrix is reformed and reduced and the calculation of the new stiffness matrix ignores the elements in the damaged area. With further load increase the damaged area grows, and new stiffness matrices are recalculated. The relation between increasing load and displacement tends to be nonlinear. This non-linearity in the (stress vs displacement) diagram continues until no further damage is possible and the stiffness matrix remains constant and the graph becomes linear again. This point will be considered the failure point of the laminates.

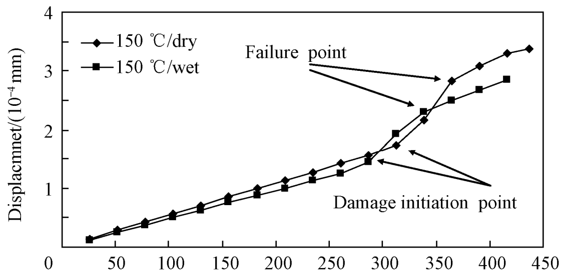
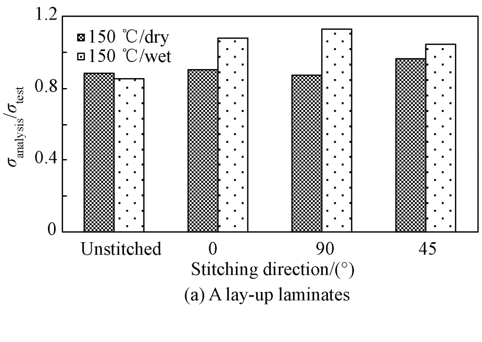


Fig. 15 Stress vs displacement diagram for A lay-up 0° stitched laminates under compression.

Figure 16 illustrates the predicted compression strength of the laminates A, B and C with different



(a) A lay-up laminates

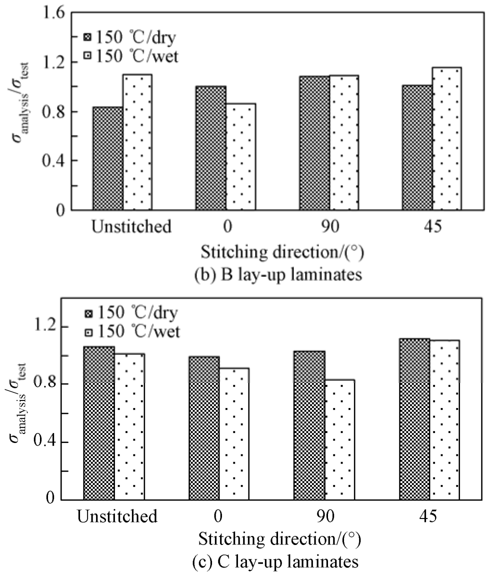


Fig. 16 Compression strength.

stacking, normalized to the test results of compression strength for each laminates under the same condition.

4.4. Prediction of tensile strength

The predicted results for tensile strength of the laminates with 150 ºC/wet compared with the test results are illustrated in Fig. 17. Analytical results are in very good agreement with the test results. The relative error is 13% for unstitched laminates, whereas it is less than 5% for stitched laminates.

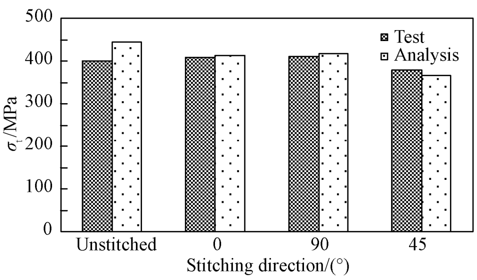


Fig. 17 Tension strength for A lay-up laminates.

4.5. Prediction of open-hole tensile strength

The predicted results for open-hole tension strength of the laminates under 150 ºC/dry, 150 ºC/wet and 20 ºC/wet normalized with the test results are illustrated in Fig. 18. Analytical results are in a very good agreement with the test results. The relative error is around 5% for all laminates in different environments.

4.6. Prediction of open-hole compressive strength

Laminated composites containing a cutout usually go through a very complicated damage process before ultimate failure, especially under compression load [18]. The classical failure criterion is developed for uniform

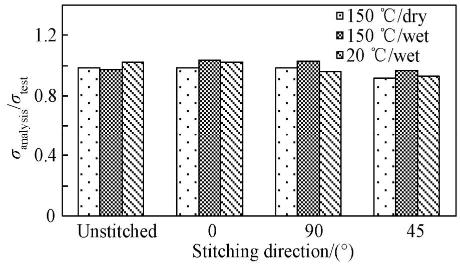


Fig. 18 Open-hole tensile strength for A lay-up laminates.

stress and therefore, it may not provide accurate results for the prediction of the open-hole compressive strength of laminates, having stress concentration on the hole edges. So, using FEA model with modified properties, the point stress criterion is applied for the prediction of open-hole compressive strength. The assumption of point stress criterion is that failure occurs when the stress σ_y over some distance d_0 away from the opening is equal or greater than the strength σ_0 of the unnotched laminate:

$$\sigma_{y(x,o)}\,|_{x=R+d_0} = \sigma_0 \tag{20}$$

where R is the open-hole radius.

In order to apply this criterion, d_0 for each laminate should be determined first. The value of d_0 (0.9 mm) was obtained by experiments in a separate research work [14]. d_0 also includes stitching effect since it was obtained from the open hole tension test of stitched laminates with various hole diameters [14]. Figure 19 shows the stress along the transverse direction away from the hole edge. Predicted and tests results of open-hole compressive strength for the laminates with 150 ºC/wet are illustrated in Fig. 20.

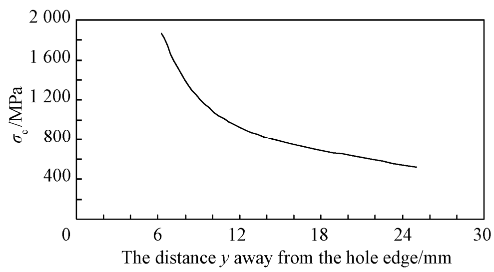


Fig. 19 Stress σ_y over the distance from the hole edge for A lay-up laminates.

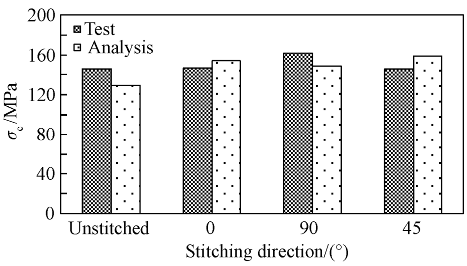


Fig. 20 Open-hole compressive strength for A lay-up laminates, 150 °C/wet.

The analysis results are found to be in a good agreement with test results. The relative error between the two results is around 11% for unstitched laminates and 5%-8 % for the stitched laminates.

5. Conclusion

Test results have shown that the compressive strength is decreased to around 15% for composites with A and B lay-up sequence and to 20% for C lay-up sequence under 150 ºC/dry. Under hygrothermal environment (150 ºC/wet), the compressive strength of the A and B laminates decreases to around 25%. For the laminates with C lay-up, the hygrothermal environment has a severe effect on the compression strength and the reduction reaches up to 45%.

Stitching might improve the compressive failure strength of the composite laminates under room temperature (20 ºC/dry) condition. However, under hygrothermal (150 ºC/wet) condition, compressive strength of stitched laminates may either be improved or reduced depending on the ply orientation and the lay-up.

As compared to the unstitched laminates, stitching improves the open-hole compressive strength of the laminates with A and B lay-up at high temperature and that with C lay-up under hygrothermal environment. The improvement reaches up to 10% in some laminates which implies that the ply orientation and the stacking sequence (especially of 0° plies) are the key factors for the difference of the compressive strength of the various laminates tested under different environmental conditions.

Under hygrothermal environment (150 ºC/wet), the compression strength of laminate with a hole decreases distinctly to around 30% for the unstitched laminate where it reaches up to 50 % for stitched laminates.

It is observed that a wet environment has no effect on the in-plane tensile strength of unstitched laminates, but improves the tensile strength of stitched laminates significantly.

From the open-hole tests, it is obvious that tensile strength of the stitched laminates increases compared to the unstitched laminates in the same environment. The open-hole strength is not sensitive to the environment and the stitch direction.

The analytical results of the tensile strength of the stitched laminates under different conditions are in a good agreement with the test, and the relative error in all cases is less than 15% compared with tests. For the tension strength the relative error is 12% for unstitched laminates, whereas it is less than 5% for stitched laminates.

The predicted results for tensile strength of the laminates under 150 ºC/wet are in a very good agreement with the test results. The relative error is 13% for unstitched laminates, where it is less than 5% for stitched laminates.

Tensile strength of the laminates with open-hole is predicted in different environments using the same code. The predicted results for tension strength of the laminates with open hole under 150 ºC/dry, 150 ºC/wet and 20 ºC/wet are in a very good agreement with the test results. The relative error is around 5% for all laminates in different environments.

Point stress criterion is applied to the prediction of the compressive strength of laminates, using the FEA with modified properties. Analysis results match well with experimental test results. The relative error between the two results is around 11% for unstitched laminates and between 5%-8% for the stitched laminates.

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